P. R. K. Chetty*, K. Kasturirangan* & B. S. Sonde**

Reliability and failure mode analysis of Aryabhata Power System

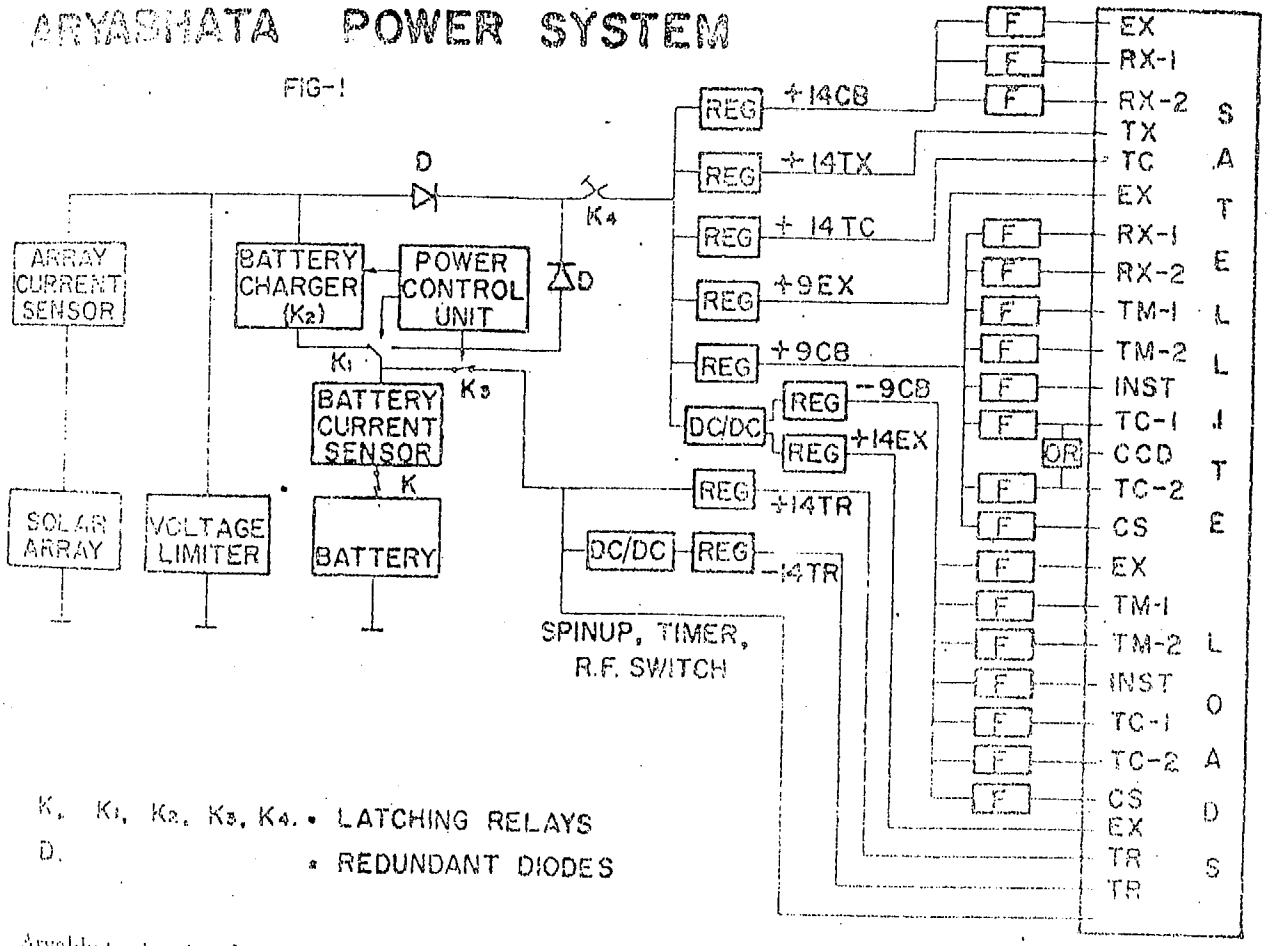
High performance, high levels of reliability and lower costs are the primary considerations in designs of satellite power systems. To provide a measure of inherent reliability of the power system, a reliability analysis is performed. The failure rates used are from MIL-HDBK-217A. Detailed reliability calculations for solar array, storage battery and power conditioning and control electronics are given. Reliability fall curve during six months life is drawn. Among the solar array, the storage battery and the electronics the reliability of the electronics is the highest.

I Introduction

The power system as a subsystem in the spacecraft assumes permanent importance as it is identified as the sole feeder of power for the entire spacecraft subsystems throughout its life. In short, it is the power system which brings the spacecraft into life and keeps it alive. Design of power system is one of the challenging problems and it has received great deal of attention since the advent of space Age. The problem becomes more acute in case of long duration space missions, where high performance, high levels of reliability and lower cost, are

ARYABHATA POWER SYSTEM

FIG-1



K, K1, K2, K3, K4. • LATCHING RELAYS

D. • REDUNDANT DIODES

Aryabhata is aimed at acquiring the technology of a satellite establishing reliable up and down communication links, proper housekeeping and development of structure and materials for space conditions. One can envisage the cases where-in certain equipments/units fail without affecting the mission. The nature of failures and their consequences on the mission goal are tabulated.

* ISRO Satellite Centre, A-1-6 Peenya, Industrial Estate, Peenya-562140, Bangalore.
** ECE Department, I.I.Sc. Bangalore-560-012.

the primary considerations. In view of these factors, reliability and failure mods analysis of Aryabhata Power System are carried out and conclusions are drawn with regard to the possible areas of improvements in the system concepts.

II Aryabhata Power System

The power requirements of Aryabhata are met by a silicon Solar cell and Ni-Cd rechargeable battery system. During the sunlit portion of the orbit, the solar cells power the subsystems and also charge the battery. The battery comes into action during the orbital eclipse. It also meets the peak demands when the power requirement exceeds the solar array capability. The power conditioning circuits are designed to match the electrical output of the energy sources to cater to the needs of various subsystems. The power outputs were available as + 14 and ± 9 volt bus voltages with r regulation better than 1%. The positive bus voltages were provided directly through high efficiency switching regulators whereas negative voltages were generated by DC/DC converters followed by switching regulators. Few of the subsystems have separate common regulators. In such cases protective devices (failsafe units) were incorporated to isolate the malfunctioning subsystem from the main line.

The power control unit provides smooth change over of power from solar array to battery and vice versa, switching over between normal charge/trickle charge modes and to switch off power to all subsystems in case of excessive discharge from the battery. The array voltage limiter takes care of the step increase in array voltage as the satellite emerges out of the eclipse zone, so as to protect the power conditioning units. Two current sensors are employed to measure the solar array current and battery charge/discharge currents.

Fig. 1 shows the basic features of the Aryabhata Power system.

III Reliability Analysis

To assess the inherent reliability of the power system, a reliability analysis is performed. The general assumptions are (a) all the components of the individual circuits/units are considered to be equally important for proper functioning, (b) the effect of one component failure on the other component is not considered.

The MIL-SPECS of the components used in the calculations are given in the Table–2. The constant failure rate reliability is calculated by $R = e^{-\lambda t}$

Where R = the reliability
e = natural log base
λ = failure rate
t = duration in hours

Standard reliability calculation techniques are used to calculate the reliability of different series and parallel circuits/units; the reliability of the entire power system is obtained by taking the reliabilities of all the circuits/units in series.

For series calculations

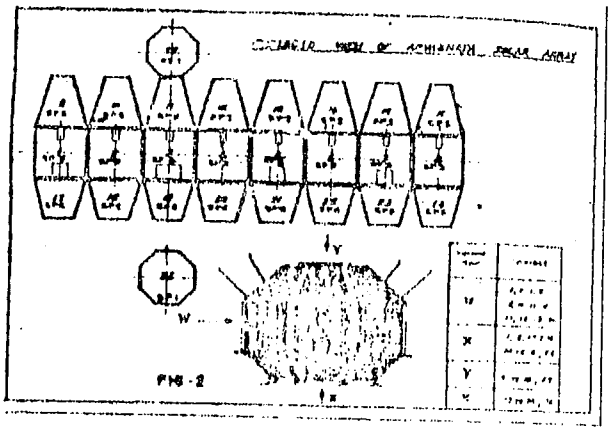
R series = (R1) (R2) (R3) . . . . (Rn)

For parallel calculations

R parallel = 1 – (1-R1) (1-R2) (1-R3). (1 Rn)

where R1, R2, R3. . .Rn are the reliabilities of the circuits/units that are in series or parallel, respectively.

III.1 *Solar Generator*: An exploded view of solar panels is shown in Fig. 2 Depending upon the orientation of the satellite to the sun the number of panels



which contribute power to the satellite vary. The maximum number of panels are exposed from the direction (W) and hence the reliability calculations are made for this case.

Solar panel type SP-2 (Fig. 3a) has got three strings in each panel with 97 cells in series and 3 cells in parallel. Solar panel type SP-6 has got three strings in each panel with 97 cells in series and 2 cells in parallel. Solar panel type SP-3 has three strings in each panel with 80 cells in series and 5 cells in parallel in two strings and 4 cells in parallel in the last string. Solar panel type SP4 has three strings with 90 cells in series and 4 cells in parallel. Solar panel type SP5 has strings with 81 cells in series and 3 cells in parallel.

The connection shown in dotted lines in types SP3, SP4, SP5. (Fig. 3b, 3c) are neglected in the reliability calculations for simplicity, hence the actual Reliability will be more than the calculated. The APPENDIX A gives the detailed reliability calculation for the entire solar generator. The reliability with an acceptable power loss of 3% is 0.9381-1802.

III.2 *Ni Cd Battery*: The battery consists of 20 Ni-Cd cells of 10AH capacity connected in series. The important point is to determine whether the Battery, during its complete period of operation, is outside of the wearout failure i.e., within the chance failure, constant failure region only.

The batteries are subjected to 2740 charge/discharge cycles approximately in six months with only about 5% depth of discharge (i.e. 10AH to 9.5AH). For the temperature excursions on board (0°–30°C),

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the wearout region starts beyond 8500 cycles, for the same depth of discharge. Hence, for the mission life of 6 months, the Battery operates out of wearout failure region and is not subjected to accidental failure.

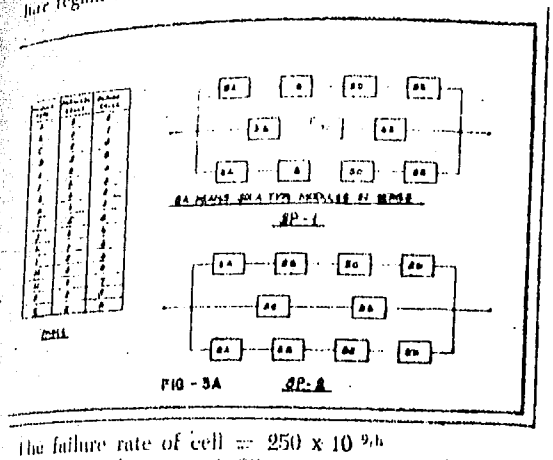


FIG - 3A

The failure rate of cell = 250×10^{-9}/h

Derating factor = 0.35

The failure rate of soldering connection in connecting the cells in series is assumed to be negligible.

$$\lambda t = 20 \times 250 \times 10^{-9} \times 4400 \times 0.35$$

$$R = e^{-\lambda t} = 0.99232957$$

III 3 *Power Conditioning and control Electronics.* Tables 2 three 5 show the reliability calculations of main power conditioning and control Electronics.

III 4 *Power System.* The Fig 4 shows the Aryabhata Power System Reliability diagram and Fig. 5 shows Reliability fall curve during its six months life.

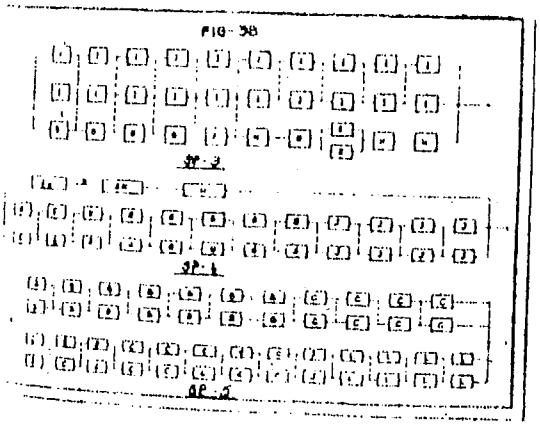


FIG- 3B

IV Failure Mode Analysis

To realize the complete mission goal, all the subsystems for which the reliability analysis have been carried out are essential. One can equally envisage the cases where certain equipments fail without affecting the complete satellite and hence can partially, fulfill the mission goals.

Aryabhata is aimed at acquiring the Technology of design, fabrication and qualification of a satellite viz. establishing reliable up and down communication links, controlling the systems for proper housekeeping including stability by spin control, thermal control, change over among redundant units and developing the structure and the materials that can withstand space conditions.

The Table 6 shows the nature of failures, consequences on the mission goal and on other subsystems.

V. In-Orbit Performance

In this connection, a short summary of the inorbit performance of Aryabhata specially in relation to the power system behaviour is of relevance. The performance of the overall power system as evaluated from the available data during the first one year in 'orbit' is satisfactory. The performance of the different power conditioning units has been as per the design calculations. The power generation from the solar panels as deduced from the data for different parts of the year as well as different temperature conditions of the orbit are as per the earlier estimates. Only one malfunction occurred which was in relation to a + 9V regulator supplying power to the three scientific experiments. This happened in the forty-first orbit and the same resulted in the incapacitation of the scientific experiments.

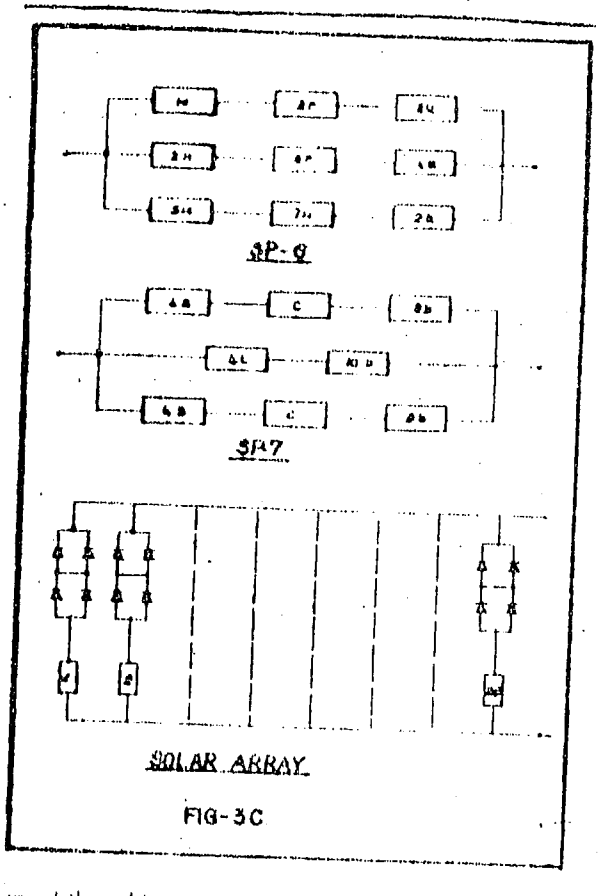
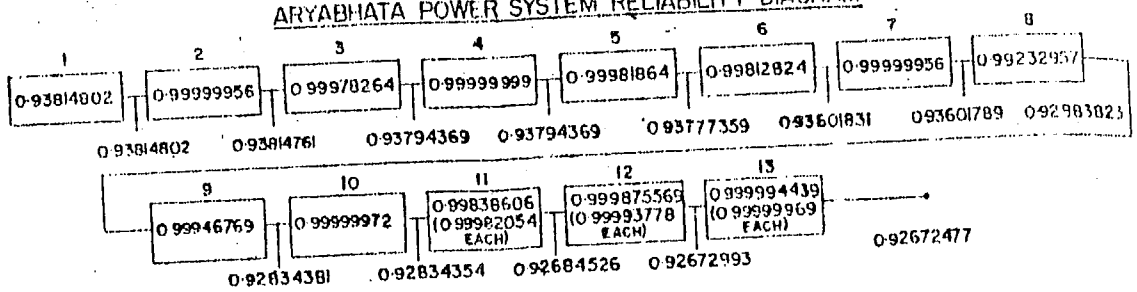


FIG-3C

ARYABHATA POWER SYSTEM RELIABILITY DIAGRAM



1 SOLAR ARRAY
2 ARRAY CURRENT SENSING RESISTER
3 VOLTAGE LIMITER
4 OR-GATE DIODES
5 BATTERY CHARGER
6 POWER CONTROL UNIT
7 BATTERY CURRENT SENSING RESISTER
8 BATTERY
9 K-RELAY
10 K4-RELAY
11 REGULATOR (1 THRU 9)
12 DC/DC CONVERTER (1 & 2)

13 FAIL SAFE CIRCUITS (1 THRU 10)

FIG-4

Post facto failure analysis was carried out to identify the possible cause of this failure. This included the effect of corona discharge from HV converter of the X-ray experiment, excessive loads at the + 9V. regulator output and worst case tests on the regulator such as maximum input voltage levels of the order of 50V, short circuiting the output and intermittant shorting of the regulator output.

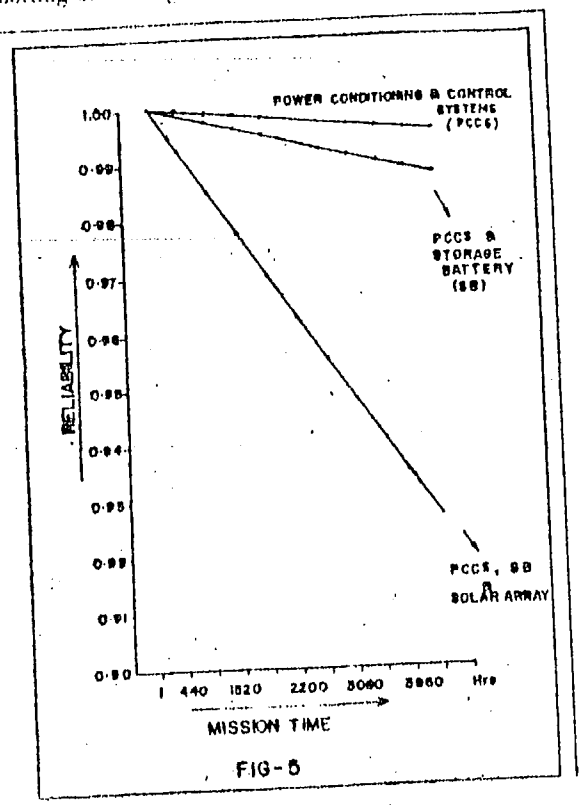


FIG-5

As none of these could lead to the observed onboard failure it was concluded that the malfunction was due to the catastrophic failure of one of the critical components possibly the series pass transistor of the regulator.

The Table 7 gives a summary of the Design Specifications and status of in-orbit performance.

VI Conclusions

Solar ARRAY: Studies carried out have shown that reliability can be improved by decreasing the module size and by providing greater number of parallel cells.

Storage Battery: In general protection/isolation diodes are to be used in cell interconnections to get high reliability. Use of redundant unit is advisable. A redundant charger is recommended.

Power Conditioning and Control Electronics: To take care of chance failures, redundancy is to be incorporated in the case of Regulators and DC/DC converters.

Reliability is of prime importance in the design considerations of the power system whose successful performance is vital to the satellite mission.

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APPENDIX–A

1. Reliability calculations are made with the following assumptions:

(i) Open circuits of solar cells occur at random with a constant failure rate. The failure rate used in these calculations is 0.002 failers per million hours.

(ii) The probability of a short circuit of an individual solar cell is negligible and taken as zero for calculations.

(iii) Failure rates of interconnections and redundant isolation diodes are negligible.

2. The success probability of any cell over 6 mths is equal to.

$$R_c = e^{-\lambda t} = e^{-2\times10^{-9}\times4400} = 0.9999912$$

$$\therefore 1 - R_c = 0.00000880$$

A module with 2 cells in parallel.

The success probability of the module with no failed cell $= R_c^2$

The success probability of the module with one failed cell $= 2R_c(1-R_c)$

The success probability of the module with two failed cells $= (1-R_c)^2$

3. Generalising the above equation, the success probability of the module with n cells in parallel and m failed cells, and connecting l such modules in series.

$$R_m = \left[\sum_{i=0}^{m} {}^{n}C_i \cdot R_c^{n-i} \cdot (1-R_c)^i\right]^l - \left[\sum_{i=0}^{m-1} {}^{n}C_i \cdot R_c^{n-i} \cdot (1-R_c)^i\right]^l \quad \text{---(A)}$$

This equation is used to evaluate the success probability of the five types of strings used (Fig. 2) for different values of m, and the results are tabulated below.

String type	Series cells	Parallel cells	Calculated Rm, for m=0	m=1	m=2	m=3
ST2	96	3	0.9974742476	0.0025575239	0	0
ST3	80	5	0.9961861188	0.0035138121	0	0
ST4	80	4	0.9971879061	0.0028120388	0	0
ST5	81	3	0.9978863860	0.0021301153	0	0
ST6	97	2	0.9983294257	0.0017057435	0	0

From this table, it is clear that the success probability of the strings with 2 or more failed cells is negligible. Hence the probabilities with no failed cells and one failed cell only are considered in the following discussion.

The worst case reliability of the solar array when maximum number of panels are exposed can be written as follows:

$$R = \sum_{i_0=M}^{M}\sum_{i_1=M}^{M}\left[{}_{12}C_i\,(Rost2)^{i_0}\,(Rist2)^{i_1}\right]\left[{}_{5}C_i\,(Rost3)^{i_0}\,(Rist3)^{i_1}\right]\times\left[{}_{5}C_i\,(Rost4)^{i_0}\,(Rist4)^{i_1}\right]\left[{}_{4}C_i\,(Rost5)^{i_1}\,(Rist5)^{i_1}\right]\left[{}_{12}C_i\,(Rost6)^{i_0}\,(Rist6)^{i_1}\right] \quad \text{----------(B)}$$

where i 0 = number of strings with no failed cells.

i 1 = number of strings with only one failed cell.

R0 ST2 = success probability of no failed cells of the string type ST2.

R1 ST2 = success probability of only one failed cell of the string type ST2.

Similarly R0 ST3, RIST3, ROST4, RIST4, ROST5, RIST5, ROST6, RIST6.

The percentage loss in power output of the solar array when 0, 1, 2 or 3 strings having only one failed cell is calculated as below: As the absolute valve of power loss of solar array is not important here, it is reasonable to assume the power output of any string to be proportional to the total number of cells employed in series and parallel connections of that string i.e.,

Power output = K (N x P) Watts

Where K = Constant of proportionality

S = Number of series cells in a string

P = Number of parallel cells in a string

Thus, the power output of the solar array for the worst case considered above is given by

Power output = (90x3)12 + (80x5)14 + (80x4) 5+ (81x3)14 + (97x2)12 K Watts.

= 9956 K watts.

If there is any string having even one failed cell, then that complete series connection of cells is unable to supply power. Thus, if a string has 97 cells in series, 3 cells in parallel and has even one failed cell in the series link, then the power loss is 97 K Watts. In a similar way, the output of the

array is calculated for 0, 1, 2 or 3 strings having one failed cell each and are tabulated below

Number of strings having one failed cell in each	Power output (xK Watts)	Normalised power output with respect to all strings having no failed cell (%)
0	9950	100
1	9950-97 9950-80	99 0 99 2
2	9950-194 9950-160	98 1 98 4
3	9950-291 9950-240	97 0 97 5

The power output has minimum and maximum values in each case as the failed cell can be in anyone of the five types of strings.

The following table gives the success probability of the solar array having 0, 1, or 3 strings with one failed cell each, calculated using eq. B.

Total number of strings i = 1 to 37 ref eq (B) i	i	Success probability of Solar Array	Normalised Power output with respect to all strings having no failed cell (%)
37	0	0.91582535	100
36	1	0.92360734 0.93761547	99 to 99.2
35	2	0.92369252 0.93814462	98.1 to 98.4
34	3	0.92369270 0.92814892	97.0 to 97.5

From the table, it can be seen that the success probability has minimum and maximum valves in each case as the cell faiture can be in any one of the five types of strings.

TABLE-I

S. No.	COMPONENTS	TYPE	TECHNOLOGY	STYLE	MIL-SPEC	QUALITY
1.	RESISTORS	Low Power	Carbon Composition	RCR	MIL-R-39008	S
		Low Power	Metal Film	RNR	MIL-R-55182	S
		High Power	Wire wound (W.W)	RWR	MIL-R-39007	S
		Low Power	Non-W.W. Trimmer	RJ	MIL-R-22097	S
2.	CAPACITORS	Non-Polarised	Ceramic	CKR	MIL-C-39014	S
		Non Polarised	Silver Mica	CMR	MIL-C-39001	S
		Polarised	Tantalum, Solid	CSR	MIL-C-39003	S
		Polarised	Tantalum, non-solid	CLR	MIL-C-39006	S
3.	SEMICONDUCTORS	Discrete	Silicon		MIL-S-19500	JAN XV
		IC	Linear		MIL-M-38510	JAN CLASS A
		IC	Linear		MIL-STD-883	
4.	RELAYS, Latching		Electromagnetic	(SL 4754)	MIL-883 Class-B	
5.	INDUCTOR	Power Transformer and Filters.				

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TABLE–2

POWER CONTROL UNIT

Component Description	Failure Rate	Derating Factor	Number of Components	Effective Failure Rate
Resistors				
Carbon Composition	0.0045	0.01	30	0.001350
	0.0045	0.02	1	0.000090
	0.0045	0.03	1	0.000135
	0.0045	0.04	2	0.000360
	0.0045	0.05	1	0.000225
	0.0045	0.15	1	0.000675
	0.0045	0.16	1	0.000720
Metal Film	0.0280	0.01	10	0.002800
	0.0280	0.02	2	0.001120
Potentiometer	13.0000	0.01	3	0.390000
Capacitors				
Tantalum, solid	0.1100	0.37	2	0.081400
Ceramic	0.1000	0.28	8	0.224000
Silver Mica	0.0030	0.28	3	0.002520
Diodes				
Rectifier	1.7000	0.01	9	0.153000
	1.7000	0.03	6	0.306000
Zener	2.7000	0.01	4	0.108000
	2.7000	0.18	1	0.486000
Transistors				
NPN, Si	2.8000	0.01	17	0.476000
	2.8000	0.30	6	5.040000
	2.8000	0.33	1	0.924000
IC (μA 741)	30.0000	0.04	3	57.600000
Relay (Latching)	120.0000	1.00	3	360.000000
	Total Failure Rate			425.798395

TABLE–3.

DC-DC CONVERTER

Component description	Failure Rate	Derating Factor	Number of Components	Effective Failure Rate
Resistors				
Carbon composition	0.0045	0.04	2	0.000360
	0.0045	0.05	1	0.000225
	0.0045	0.06	1	0.000270
	0.0045	0.16	1	0.000720
	0.0045	0.20	1	0.000900
Capacitors				
Tantalum, solid	0.1100	0.53	1	0.058300
Tantalum, wetslug	0.1500	0.53	2	0.159000
Ceramic	0.1000	0.80	4	0.032000
Diodes				
Rectifier	1.7000	0.25	4	1.700000
Zener	2.7000	0.03	1	0.081000
Transistors				
NPN, Si	2.8000	0.33	2	1.848000
PNP, Si	4.2000	0.30	1	1.260000
Inductor	7.5000	0.60	1	4.500000
Transformer (One secondary)	7.5000	0.60	1	4.500000
	Total Failure Rate			14.140775

FAIL-SAFE

1. Resistors					
Carbon composition	.. ..	0.0045	0.01	2	0.000090
		0.0045	0.03	1	0.000135
2. Transistors					
PNP, Si	.. ..	4.2000	0.01	1	0.042000
NPN, Si	.. ..	2.8000	0.01	1	0.028000
		Total Failure Rate			0.070225

MISCELLANEOUS

1. Current sensing Resistor	.. ..	0.2000	0.50	1	0.1000
2. OR-Gate diode Rectifier	.. ..	1.7000	0.50	4	0.0000
3. Isolation diode Rectifier	.. ..	1.7000	0.16	(Two in parallel) (See Fig. 3C)	—

TABLE—4

BATTERY CHARGER

Component Description		Failure Rate	Derating Factor	Number of Components	Effective Failure Rate
1. Resistors					
Carbon composition	.. ..	0.0045	0.01	10	0.000450
		0.0045	0.03	1	0.000135
		0.0045	0.04	1	0.000180
		0.0045	0.06	1	0.000270
		0.0045	0.07	3	0.000945
		0.0045	0.08	1	0.000360
		0.0045	0.12	2	0.001080
Wire wound	.. ..	0.0600	0.05	2	0.006000
		0.0900	0.25	2	0.045000
Potentiometer	.. ..	13.0000	0.01	2	0.260000
2. Capacitors					
Tantalum, solid	.. ..	0.1100	0.12	1	0.013200
		0.1100	0.50	1	0.055000
Tantalum, wetslug	.. ..	0.1500	0.38	2	0.114000
Ceramic	.. ..	0.1000	0.70	2	0.140000
3. Diodes					
Rectifier	.. ..	1.7000	0.40	1	0.680000
Zener	.. ..	2.7000	0.11	1	0.297000
		2.7000	0.02	1	0.054000
4. Transistors	.. ..				
PNP, Si	.. ..	4.2000	0.02	1	0.084000
		4.2000	0.04	1	0.168000
		4.2000	0.40	2	3.360000
		4.2000	0.53	1	2.226000
NPN, Si	.. ..	2.8000	0.16	1	0.448000
		2.8000	0.30	1	0.840000
		2.8000	0.33	1	0.924000
5. IC (λA741)	.. ..	30.0000	0.90	1	27.000000
6. Inductor	.. ..	7.5000	0.60	1	4.500000
		Total Failure Rate			41.220620

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TABLE–5.

REGULATOR

Component Description	Failure Rate	Derating Factor	Number of Components	Effective Failure Rate
1. Resistors				
Carbon Composition	0.0045	0.01	8	0.000270
	0.0045	0.04	1	0.000180
	0.0045	0.05	1	0.000225
	0.0045	0.07	1	0.000315
Metal Film	0.0250	0.01	1	0.000250
Wire wound	0.0000	0.10	1	0.000000
Potentiometer	13.0000	0.01	1	0.130000
2. Capacitors				
Tantalum, solid	0.1100	0.11	2	0.024200
Tantalum, wetslug	0.1500	0.19	2	0.057000
	.1500	0.53	1	0.079500
Ceramic	0.1000	0.07	1	0.007000
3. Diodes				
Rectifier	1.7000	0.40	1	0.680000
Zener	2.7000	0.02	1	0.054000
	2.7000	0.05	1	0.135000
4. Transistors				
PNP, Si	4.2000	0.40	2	3.360000
	4.2000	0.04	1	0.168000
	4.2000	0.02	1	0.084000
5. Inductors	7.5000	0.60	2	9.000000
6. IC (μA711)	30.0000	0.90	1	27.000000
	Total Failure Rate			40.785970

LIMITTER

1. Resistors				
Carbon Composition	0.0045	0.01	10	0.000450
	0.0045	0.02	2	0.000180
	0.0045	0.03	1	0.000270
	0.0045	0.04	2	0.000360
	0.0045	0.05	1	0.000225
	0.0045	0.07	1	0.000315
	0.0045	0.10	3	0.001350
	0.0045	0.21	1	0.000945
Wire wound	0.0900	0.26	3	0.070200
2. Diodes				
Zener	2.7000	0.01	3	0.081000
	2.7000	0.02	1	0.054000
	2.7000	0.08	1	0.216000
3. Transistors				
PNP, Si	4.2000	0.02	1	0.084000
	4.2000	0.20	1	0.840000
NPN, Si	2.8000	0.13	2	0.728000
	2.8000	0.33	2	2.288000
4. IC (AD 108)	30.0000	0.50	3	45.000000
	Total Failure Rate			49.405295

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TABLE–6

System	Failure modes	Effects on other systems and consequences on the mission goal.
Battery	Open	Tape recorder operation change over to redundant transmitter, further spin up operation will not be possible.
	Short	Power will be shunted to ground. Tape Recorder operation, change over to redundant transmitter and further spin-up is not possible.
Charger	Open	Isolation of storage Battery from charging. Tape Recorder will not function. Hence satellite can work only in real time mode. Also as power is cut to Transmitter change over circuit, redundant Transmitter cannot be used. Further spin up is also not possible.
Power Control Unit:		
i) Charge|discharge relay	Charge mode	Satellite will work only during orbital day.
ii) Emergency relay	Discharge mode	Equal to Battery opening (the effects of this are given above).
	Normal mode	Much care has to be taken in draining the battery which can be effected by commanding.
	Emergency mode	Equal to Battery getting isolated.
iii) Charge|trickle relay	Charge mode	Danger of Battery failure as overcharge results in high pressure build up in the Battery.
	Trickle charge mode	Battery cannot be charged in the stipulated time and Battery gets discharged in few cycles even the drain is minimised as only experiments and Tape recorder can be put off.
Limiter	Short	Solar array is shorted to ground.
	Open	Solar array voltage will raise alongwith the V-I characteristics of the solar array. This may result in high input voltages to regulators which is not expected.
Failsafes	One failsafe is provided in series with every subsystem, the subsystems themselves being loads in parallel to the regulator. As long as the particular subsystem behaves properly a short circuit mode of failure of the corresponding failsafe does not matter all. When the failure is an open, subsystem simply gets disconnected and draws no power.	Other subsystems remain unaffected. If a particular subsystem misbehaves (draws more current), a short circuit mode of failure results in cutting the power to the subsystems which are connected to the same regulator. The redundancy provided in the subsystems e.g., receiver I & II (having secause this not a one for one redundancy.
Regulator (+14 CB)	Complete failure resulting in no poweroutput.	Experiments and both receivers inoperative. Telecommand link gets cut off.
Regulator (including DC|DC) (–14 EX)	Complete	Experiments in operative.
Regulator (including DC|DC) (–9 CB)	Complete	Experiments, INST, TM & TC inoperative resulting in uplink cut off and no data but for Transmitter carrier.
Regulator (+9 EX)	Complete	Experiments inoperative.
Regulator (+9 CB)	Complete	Receiver, TM, TC, Instrumentation inoperative resulting in uplink cut off and no data but for TX carrier.
Regulator (+14 TX)	Complete	No down link. No radio tracking. Total failure of the mission.
Regulator (+14 TC)	Complete	Command relays inoperative. No uplink.
Regulator +14TR OR –14 TR including (DC|DC)	Complete	Tape Recorder inoperative, only real time Transmission of data possible.

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